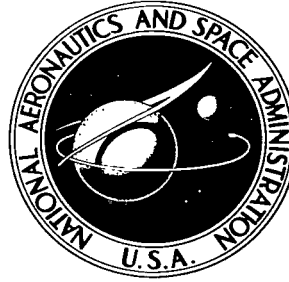


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INFLUENCE OF CRYSTAL STRUCTURE ON THE FRICTION AND WEAR OF TITANIUM AND TITANIUM ALLOYS IN VACUUM

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and Robert L. Johnson*

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SUMMARY

The friction and wear characteristics were determined in vacuum (to 10^{-9} mm Hg) for titanium and titanium alloys sliding on themselves and on 440-C stainless steel. The titanium alloys included titanium-tin, titanium-oxygen, and titanium-zirconium. The influence of tin and oxygen on the lattice parameters of titanium and its friction and wear characteristics were measured. The effect of crystal transformation from a hexagonal to a cubic form for a zirconium-titanium alloy was also studied. Friction and wear experiments were conducted with a hemispherical rider sliding on a flat disk surface at loads to 1000 grams and speeds to 2250 feet per minute. Experiments were conducted at 75° and 425° F.

While most hexagonal metals have good friction and wear properties, the results of this investigation indicate that titanium, although a hexagonal metal, exhibits relatively high friction. This high friction may be related to a difference in the slip mechanisms for titanium; titanium unlike most hexagonal metals slips on the $\{10\bar{1}0\}$ planes rather than on the (0001) basal plane.

The addition of tin or oxygen to titanium expands the crystal lattice of titanium and reduces the friction and wear characteristics. The friction coefficient obtained for a titanium-zirconium alloy markedly increased; complete seizure occurred when the material transformed from the hexagonal to the cubic form.

INTRODUCTION

Metals with hexagonal structure have superior friction and wear characteristics in comparison with the cubic structure metals (refs. 1 to 4). (Metals which crystalize in the hexagonal or cubic form will be referred to herein as hexagonal metal and cubic

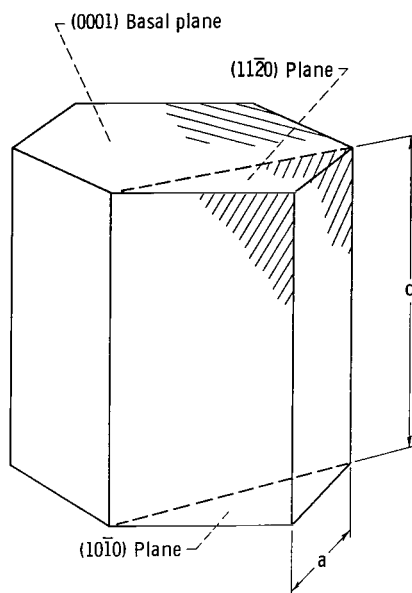


Figure 1. - Hexagonal crystal.

metal, respectively.) Further it is demonstrated in references 2 to 4 that for those metals which undergo crystal transformation (the hexagonal structure being one form) much better friction and wear characteristics exist in the hexagonal form.

In space module and vehicle component design, titanium appears as a very attractive metal because of its high strength-to-weight ratio. It has relatively poor friction and wear characteristics, however, and as a consequence titanium alloys have not been given any really serious consideration for lubrication systems. Titanium might be considered for lubrication components if acceptable friction characteristics could be obtained.

The stability of titanium oxide and the ease with which it forms has in the past resulted in the friction and wear properties of titanium being dependent on the

surface oxides. As is well known, oxides markedly influence the friction and wear characteristics of metals. If friction and wear measurements of titanium were made in vacuum (10^{-9} mm Hg or lower), an environment similar to that of space would be provided and the presence of oxides and contaminants would be appreciably reduced.

In accordance with the adhesion theory of friction, shear and ploughing are responsible for friction. Where the roughness is negligible, the shear strength and the flow pressure are the determining factors for the friction characteristics (ref. 5).

Titanium like many other hexagonal metals (cobalt, lanthanum, thallium, etc.) undergoes a crystal transformation from a hexagonal form (alpha titanium) to a cubic form (body-centered-cubic beta titanium) at 1620°F (882.5°C). Many elements (aluminum, tin, antimony, carbon, oxygen, and nitrogen) stabilize the alpha or hexagonal crystal form of titanium, and other elements (transition) stabilize the beta or cubic form (refs. 6 and 7).

It is demonstrated in references 2 and 3 that slip along basal planes in hexagonal metals is desirable for minimum friction and wear. Unlike many hexagonal metals, titanium does not have the ideal close-packed structure required for basal shear, and the normal slip plane in titanium is not the basal plane (0001) but rather predominantly the $\{10\bar{1}0\}$ planes (refs. 8 to 11). These planes are shown in figure 1. Differences in friction for various crystal planes have been observed in cubic metals (ref. 12). Selective alloying with alpha- (hexagonal) stabilizing and lattice-expanding elements may increase the amount of basal slip. Basal slip occurs but to a lesser degree than $\{10\bar{1}0\}$ slip. A result of increasing the probability for basal slip might be improved friction and wear characteristics.

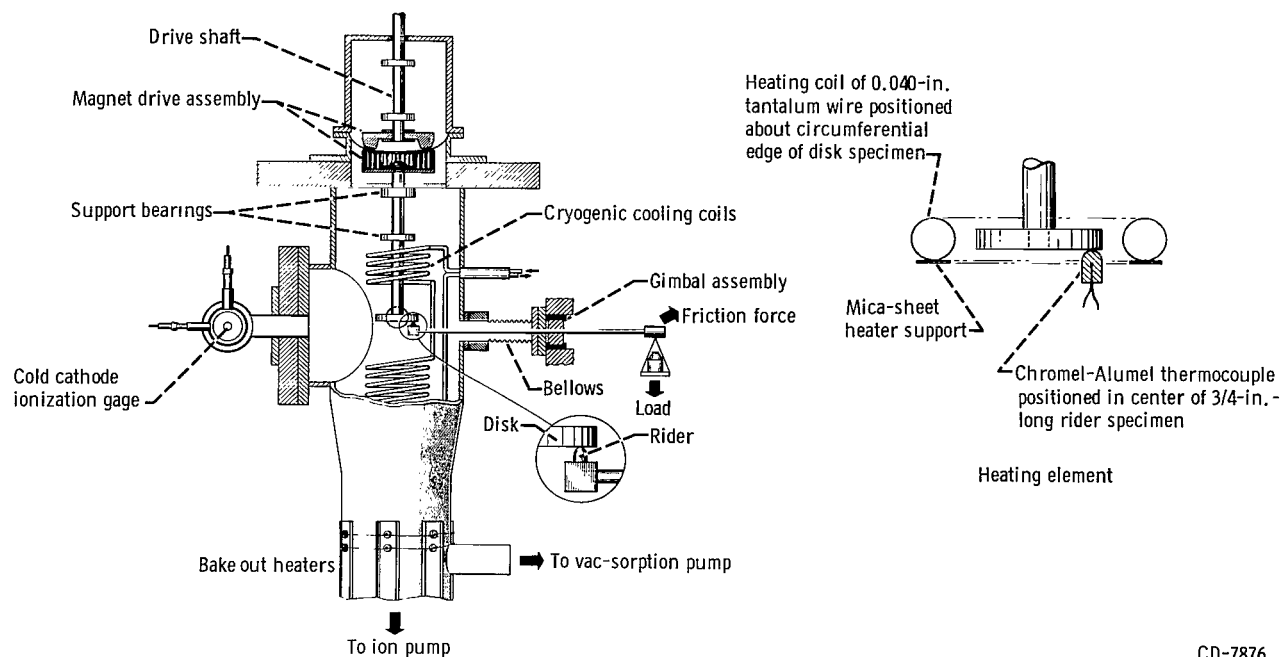


Figure 2. - High-vacuum friction and wear apparatus.

This investigation was conducted (1) to determine in vacuum the friction characteristics of titanium, (2) to expand the titanium crystal lattice and to promote basal slip by selective alloying and then to measure the effects of expansion on friction characteristics, and (3) to measure the influence of the hexagonal to cubic crystal transformation on the friction characteristics of a titanium-zirconium alloy.

ALLOY PREPARATION

The titanium alloys used in this investigation, titanium-tin, titanium-oxygen, and titanium-zirconium, were all arc-cast under reduced argon pressure. Small pieces of the metal to be cast were placed in a water-cooled copper mold and arc-melted with a tungsten electrode. The specimen was then turned over in the mold and remelted. This process was repeated a number of times to ensure homogeneity in the casting. After the alloys cooled, they were removed and metallographic, chemical analyses were made. Friction and wear specimens were then prepared. In order to ensure a maximum hexagonal form, all samples were sealed in evacuated tubes and heat-treated at 1400° F (760° C) for 72 hours.

APPARATUS

The apparatus used in this investigation is shown in figure 2. The basic elements of

the apparatus were the specimens (a $2\frac{1}{2}$ -in. -diam. flat disk and a 3/16-in. -rad. rider) mounted in a vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The drive magnet outside the vacuum system was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing (cutaway in fig. 2) and was mounted on one end of the shaft within the chamber. The end of the shaft opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm away from the rider specimen was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a vac-sorption forepump. The pressure in the chamber adjacent to the specimen was measured with a cold-cathode ionization gage. In the same plane as the specimens and ionization gage, was a diatron-type mass spectrometer (not shown in fig. 2) for determination of gases present in the vacuum system. A 20-foot, 3/16-inch-diameter stainless-steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

In experiments where external heating of the specimens was required, a wire-wound tantalum heater was placed about the circumferential edge of the disk specimen. The rider was equipped with thermocouples, and the bulk-specimen (fig. 2) temperatures were recorded. Note, these were bulk rider specimen temperatures; no attempt was made to record interface temperatures.

Specimen Finishing and Cleaning Procedure

The disk and rider specimens used in the friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and rider were given the same preparatory treatment: (1) a thorough rinsing with acetone to remove oil and grease, (2) a polishing with moist levigated alumina on a soft polishing cloth, and (3) a thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

RESULTS AND DISCUSSION

Titanium

The friction characteristics were determined for commercial-purity (99.2 percent)

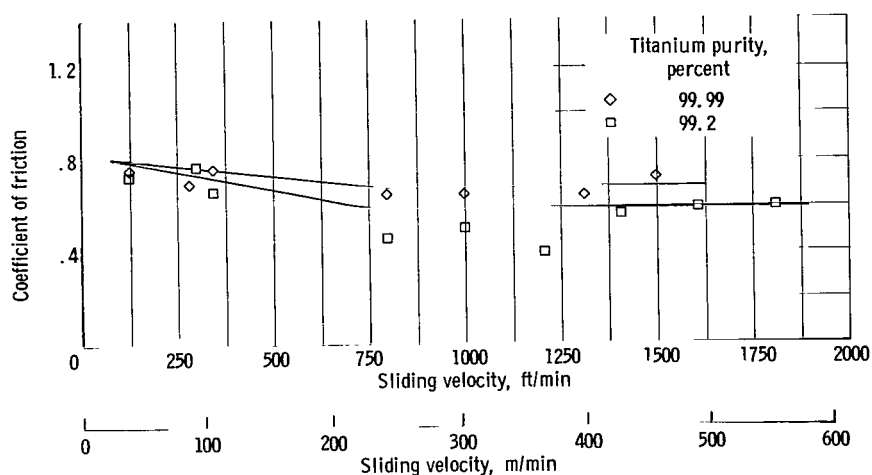


Figure 3. - Coefficient of friction for titanium sliding on titanium in vacuum (10^{-9} mm Hg) at various sliding velocities. Load, 1000 grams; no external specimen heating.

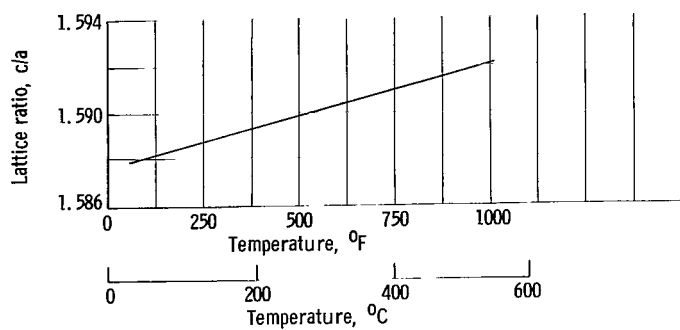
TABLE I. - CRYSTALLINE LATTICE PROPERTIES OF VARIOUS HEXAGONAL METALS

Metal	Atomic radius, Å	Interatomic distance		Lattice ratio, c/a	Slip plane	Slip direction	Critical resolved shear stress, kg/sq mm	Reference
		c, Å	a, Å					
Cadmium	1.382	5.606	2.972	1.886	(0001)	$[2\bar{1}\bar{1}0]$	0.058	13
Zinc	1.213	4.935	2.659	1.856	(0001)	$[2\bar{1}\bar{1}0]$.094	13
Magnesium	1.364	5.199	3.202	1.624	(0001)	$[2\bar{1}\bar{1}0]$.083	13
					$\{10\bar{1}1\}$	^a $[2\bar{1}\bar{1}0]$		
Cobalt	1.162	4.061	2.502	1.624	(0001)	$[2110]$.675	2
Titanium	1.324	4.729	2.953	1.587	$\{10\bar{1}0\}$ ^b	$[11\bar{2}0]$	5.0	8, 9, 10
					(0001)	$\{2\bar{1}\bar{1}0\}$	11.0	

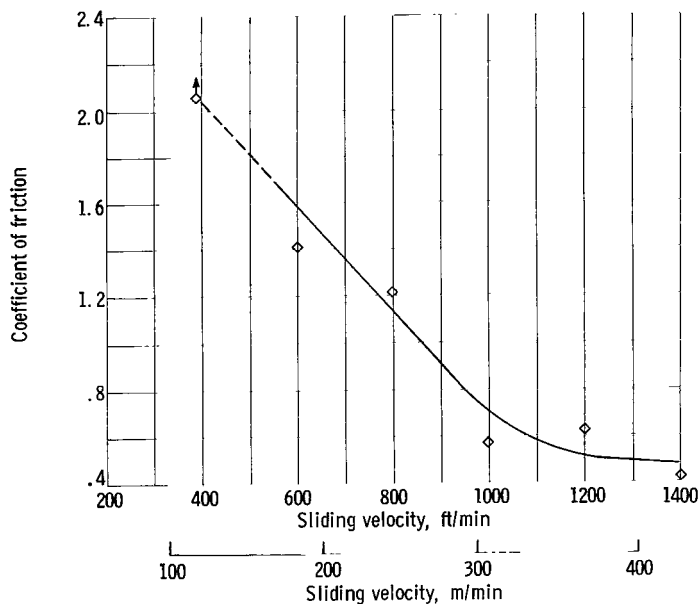
^aAt high temperature.

^bPredominantly.

and high-purity (99.99 percent) titanium metal in a vacuum environment (fig. 3). The friction coefficient decreased slightly with increase in sliding velocity; a value of about 0.6 was obtained at sliding velocities in excess of 750 feet per minute. Examination of table I indicates much higher shear stress associated with titanium in the $\{10\bar{1}0\}$ plane than with other hexagonal metals along the basal plane. In the hexagonal metals having basal glide or slip, only one plane is involved, while with titanium there are a number of $\{10\bar{1}0\}$ planes. The cubic metals possess multiple slip planes. With an increased number of possible slip systems, an increase in blocking of dislocations and strain hardening might be anticipated. Reference 13 indicates that this in fact is the case, that



(a) Expansion of lattice ratio with temperature.



(b) Change in coefficient of friction with sliding velocity.

Figure 4. - Lattice ratio c/a as a function of temperature and coefficient of friction for titanium sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external specimen heating.

lattice parameters which result in its slipping primarily on the basal plane (0001). A relatively low critical resolved shear stress (0.675 kg/sq mm) is therefore required to initiate slip (table I). In contrast, however, slip in hexagonal titanium occurs primarily in the $\{10\bar{1}0\}$ planes. The critical resolved stress to shear on these planes is 5.0 kilograms per square millimeter in compression, and, consequently, higher friction coefficients might be expected for titanium than for cobalt. Since the shear stress required for slip on the 0001 plane is 11.0 kilograms per square millimeter for titanium (ref. 8), slip on the basal plane (0001) can be initiated only with great difficulty. This high stress value may be compared with values for other hexagonal metals in table I.

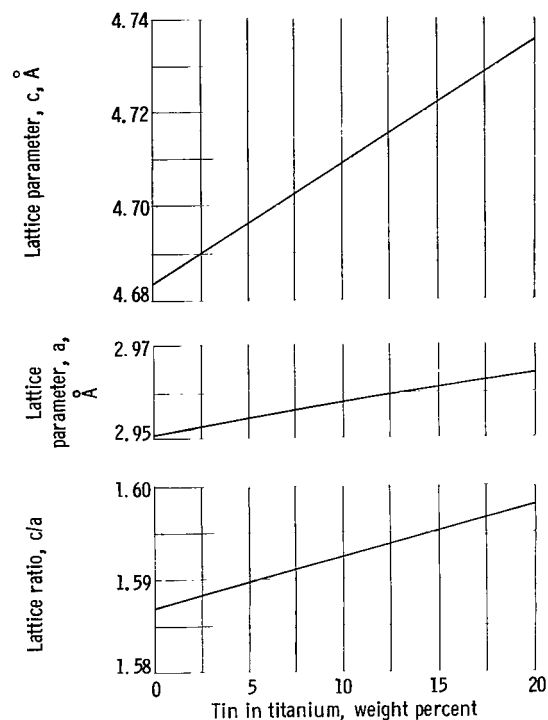
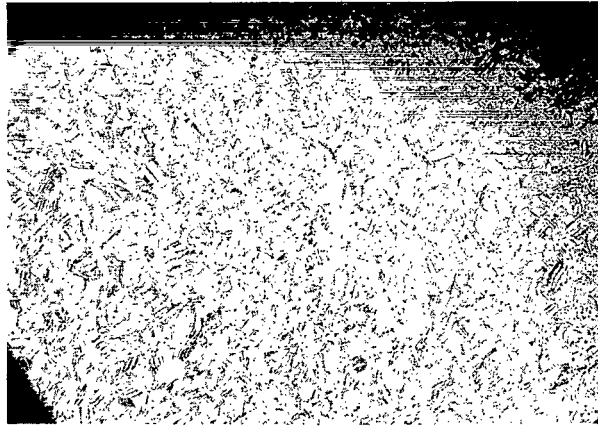


Figure 5. - Lattice parameters of binary tin-titanium alloys.

is, a high degree of strain hardening is observed for cubic metals (e. g., nickel and copper), while very little is observed for the hexagonal metals magnesium, zinc, and cadmium.

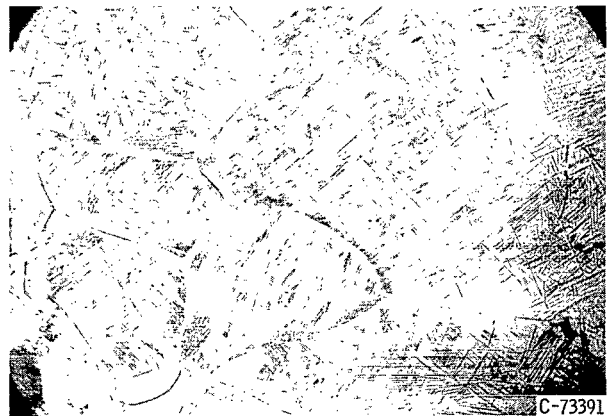
The friction coefficient for titanium is higher than that obtained with the hexagonal metal cobalt in references 2 and 3. Cobalt has crystal



(a) Cast titanium (no tin).



(b) Titanium - 5 percent tin.



(c) Titanium - 20.5 percent tin.

Figure 6. - Photomicrographs of titanium and two titanium-tin alloys. Keller's etch; X50.

The friction coefficient was also determined for 99.99-percent titanium sliding on 440-C stainless steel in vacuum (fig. 4). The friction coefficient at 390 feet per minute for hexagonal titanium sliding on cubic 440-C stainless steel was in excess of 2.0. With increasing sliding velocity, the friction coefficient began to decrease. This decrease may be related to expansion of the titanium lattice ratio with increasing temperature (fig. 4). A transfer film of titanium to 440-C was noted upon completion of the experiment; this film may influence the results observed.

Tin-Titanium

With the increase in the lattice ratio of titanium, a decrease in resolved critical shear stress may be anticipated and, consequently, a reduction in friction coefficients as is noted in figure 4. Increasing the lattice ratio in titanium may be achieved by

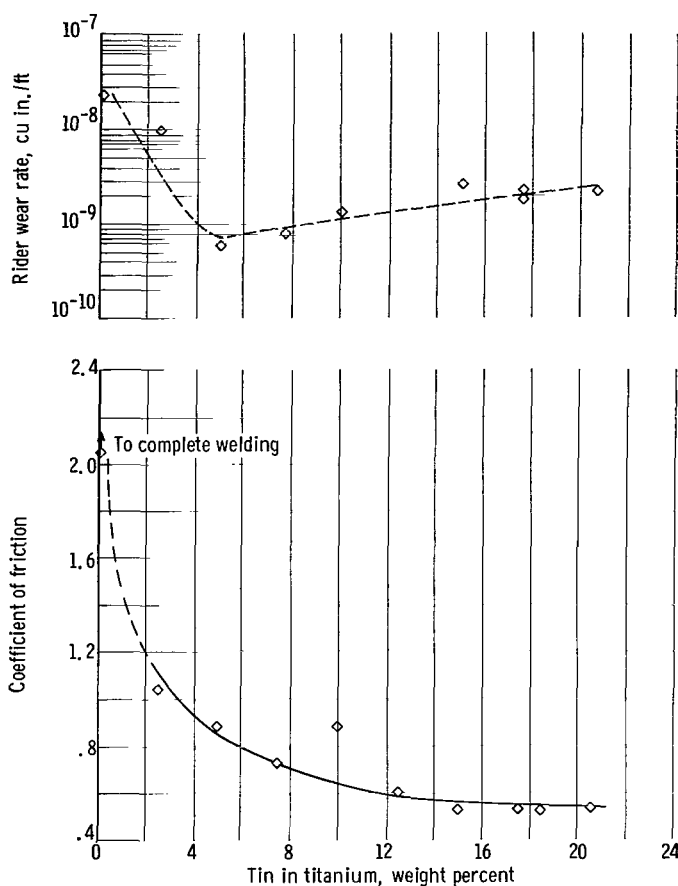


Figure 7. - Coefficient of friction and rider wear rate for titanium-tin alloys sliding on 440-C stainless steel in vacuum. Sliding velocity, 390 feet per minute; load, 1000 grams; no external specimen heating.

means other than high temperatures. For example, retaining a solid solution by adding selected alloying agents, which are alpha stabilizers, may enable expansion of the crystal lattice of titanium without increasing temperature. Examination of crystallographic parameters given in references 6 and 14 for titanium binary alloys indicates that a number of elements (e.g., oxygen, nitrogen, carbon, tin, etc.) could be added to titanium to expand the crystal lattice. Tin and oxygen appear most attractive because of the expansion characteristics gained with moderate additions of the alloying elements. These simple binary alloys are not bearing compositions; in fact, oxygen is highly embrittling.

Alloys of titanium-tin were therefore prepared. These alloys contained up to 20.5 percent tin in titanium. The effect of the addition of tin on the lattice parameters of titanium were measured with X-ray diffraction, and

the resultant effect is shown in figure 5. Photomicrographs of titanium and two of the tin-titanium alloys are presented in figure 6. With 20.5 percent tin, a solid solution was obtained; this percentage is very near the maximum solid solubility limit (at room temperature) of tin in titanium.

Friction and wear data were obtained for the tin-titanium alloys in vacuum (fig. 7). The addition of as little as 2.5 percent tin resulted in a marked decrease in friction coefficient; friction continued to decrease with the addition of tin to a concentration of 15.0 percent tin. For compositions in excess of 5.0 percent tin, very little effect of tin on wear for titanium was observed. The real significance of wear in vacuum is, however, difficult to ascertain because of a continuous transfer back and forth of wear material.

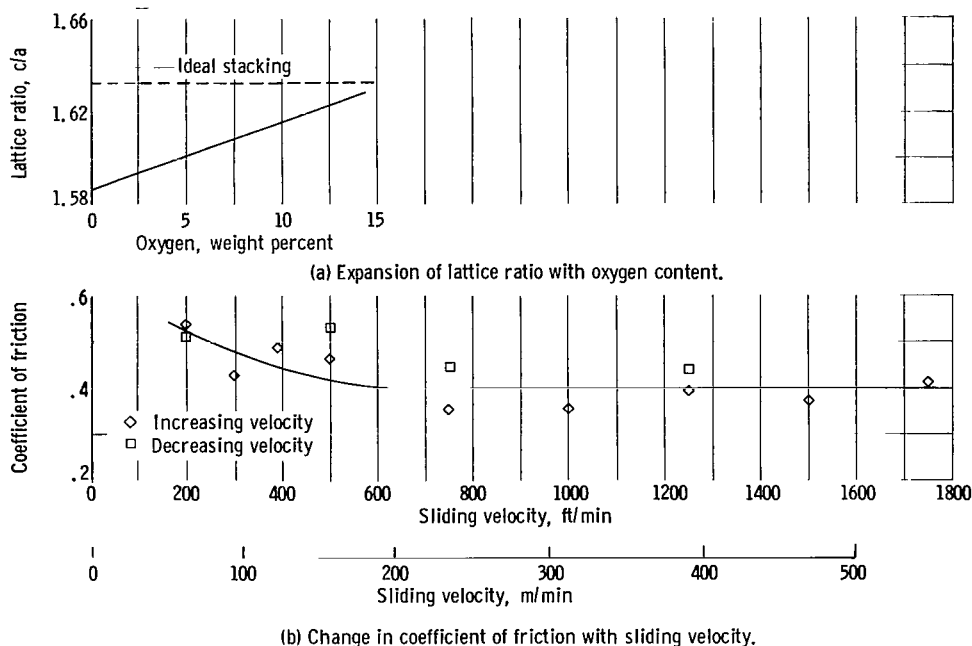


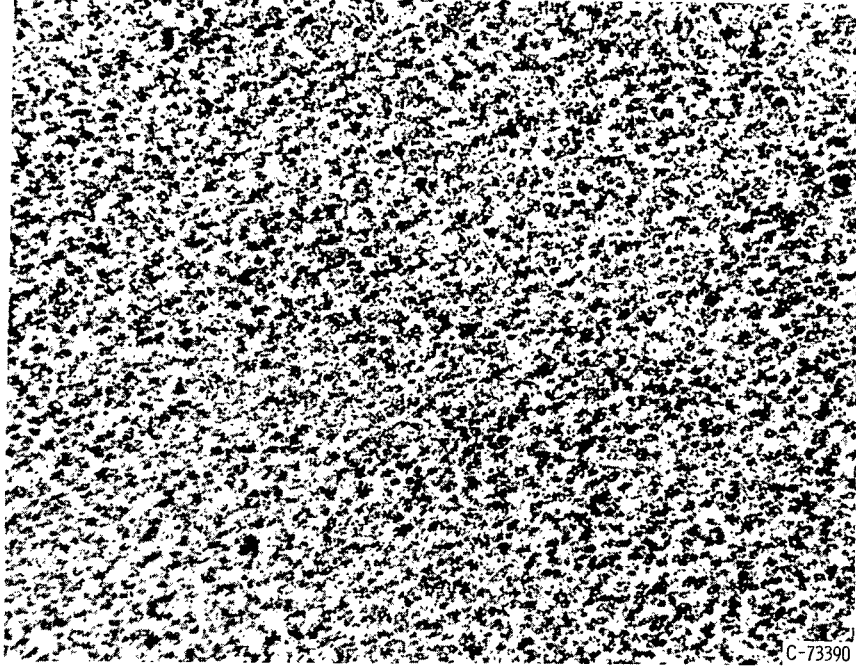
Figure 8. - Lattice ratio c/a as a function of weight percent oxygen and coefficient of friction for 10-percent-oxygen - titanium alloy sliding on 440-C stainless steel in vacuum. Load, 1000 grams; no external specimen heating.

Titanium-Oxygen

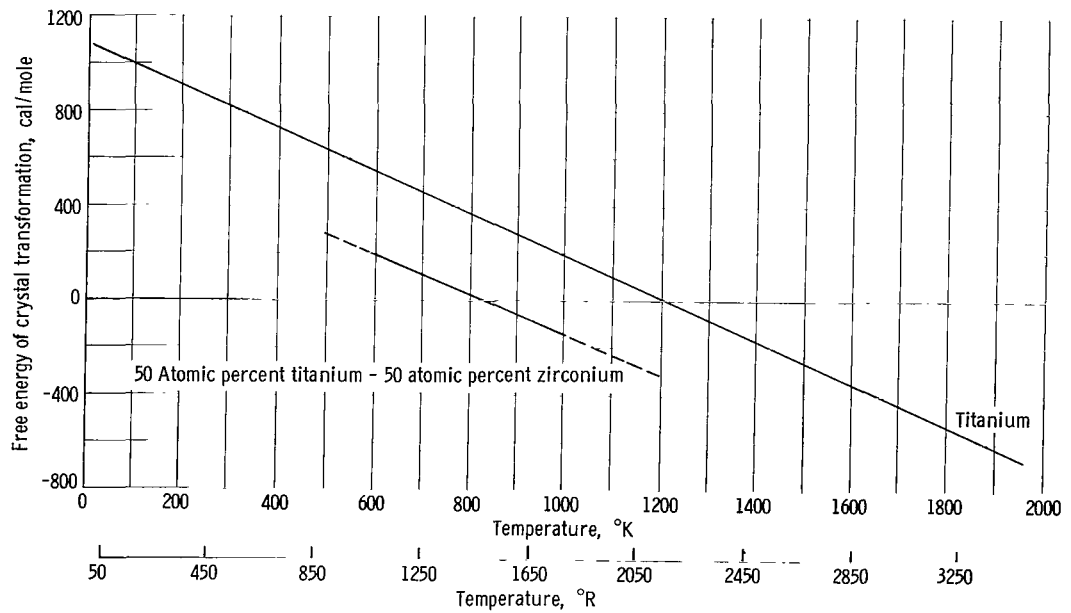
Consideration of the phase diagram indicated that the c/a lattice ratio continues to increase with the addition of oxygen to 14.5 weight percent. Alloys of oxygen in titanium were therefore prepared with 14.5 weight percent oxygen. Such alloys were very brittle and consequently oxygen concentration was reduced to 10 weight percent and below. The lattice expansion of titanium with the addition of 10 weight percent oxygen is shown in figure 8. The lattice ratio (c/a) expanded to 1.616 with the addition of the 10 weight percent oxygen; the ideal stacking sequence gives a ratio of 1.633. Friction data for the titanium-oxygen alloy are also presented in figure 8 with the alloy sliding on 440-C stainless steel at various sliding velocities. If the friction data are compared with those of figure 4 for 99.99 percent titanium sliding on 440-C, a marked decrease in friction can be seen at sliding velocities less than 1000 feet per minute.

Titanium-Zirconium

Titanium metal undergoes a crystal transformation from the hexagonal form to a



(a) Photomicrograph of arc-cast 50-atomic-percent-titanium - 50-atomic-percent-zirconium alloy. Keller's etch; X750.



(b) Free-energy data (ref. 15).

Figure 9. - Free energy associated with hexagonal-close-packed to body-centered-cubic crystal transformation of titanium and photomicrograph of titanium-zirconium alloy.

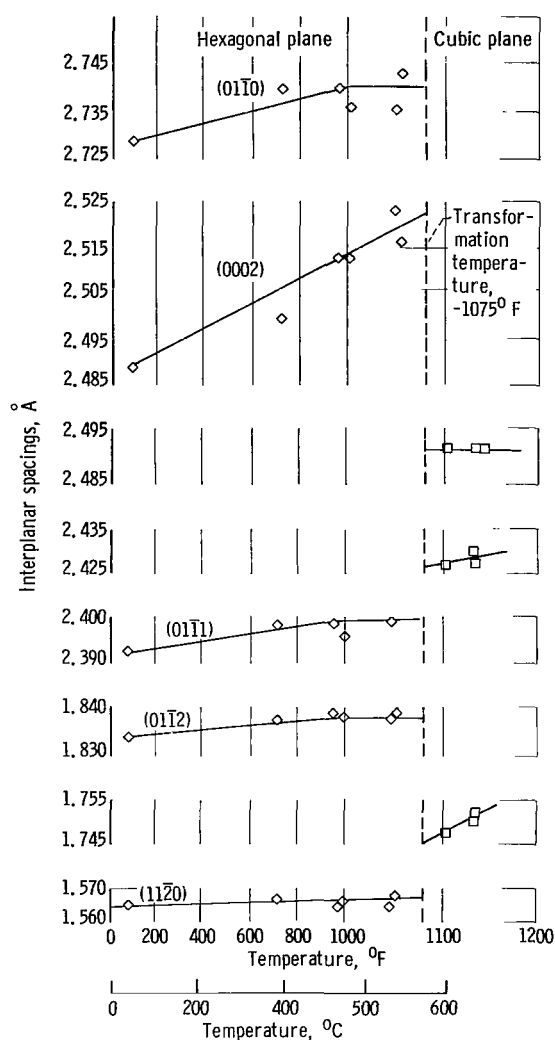


Figure 10. - Interplanar spacing for crystal transformation of 50-atomic-percent-titanium - 50-atomic-percent-zirconium alloy as measured by X-ray diffraction.

crystal transformation of titanium and an alloy of 50 atomic percent titanium - 50 atomic percent zirconium. The crystal transformation temperature for a 50-atomic-percent-titanium - 50-atomic-percent-zirconium alloy was determined experimentally as 1075° F (580° C) (fig. 10).

Friction data were obtained as a function of sliding velocity in vacuum in an attempt to achieve the transformation temperature for the rider specimen by increasing sliding velocity (fig. 11). Increasing sliding velocity resulted in a decrease in friction at sliding velocities to 2000 feet per minute. At 2250 feet per minute, a friction increase occurred. In order to obtain a definite indication of the transformation, specimens were preheated to an ambient temperature of 425° F. The results obtained in this ex-

cubic structure at about 1600° F (refs. 7, 15, and 16). Transformation from the hexagonal to the cubic form resulted in marked changes in friction for cobalt and the rare earth elements (refs. 2 to 4). Because of the relatively high temperature of the transformation of titanium, friction experiments could not readily be conducted in the vacuum friction apparatus. Friction experiments were, however, conducted in high-purity argon with induction heating. A friction change was noted with the crystal transformation. The friction coefficient was approximately 3.0 at the transformation and rose with the occurrence of complete welding at the transformation. The titanium used in this experiment was 99.99 percent pure, and the argon gas contained 2.0 ppm nitrogen and 0.2 ppm oxygen.

Examination of the literature indicates that the crystal transformation of a titanium-zirconium alloy (50 atomic percent titanium - 50 atomic percent zirconium) occurs at a considerably lower temperature than it does for pure titanium (refs. 6 and 15). Reference 15 discusses in detail the crystal transformation of titanium, zirconium, and alloys of these two elements and the thermodynamics involved. Data from reference 15 are presented in figure 9 for the free energy associated with the

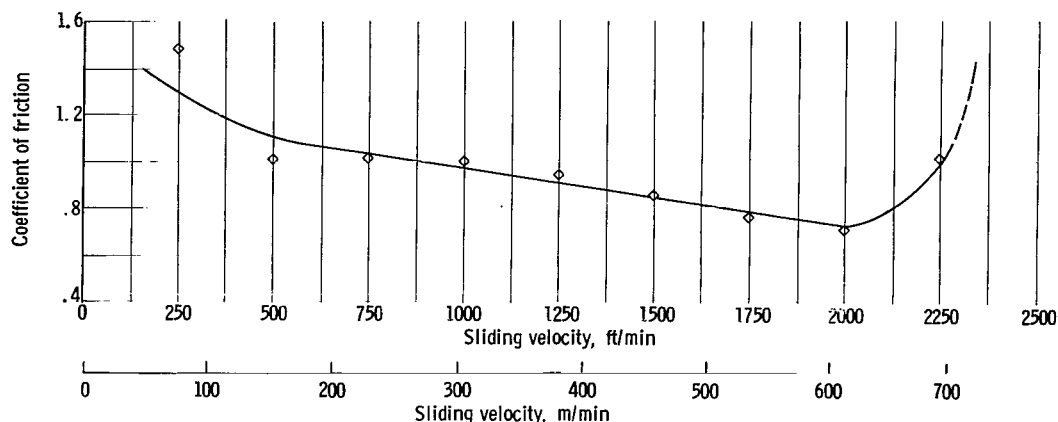


Figure 11. - Coefficient of friction for 50-atomic-percent-titanium - 50-atomic-percent-zirconium alloy sliding on itself in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external specimen heating.

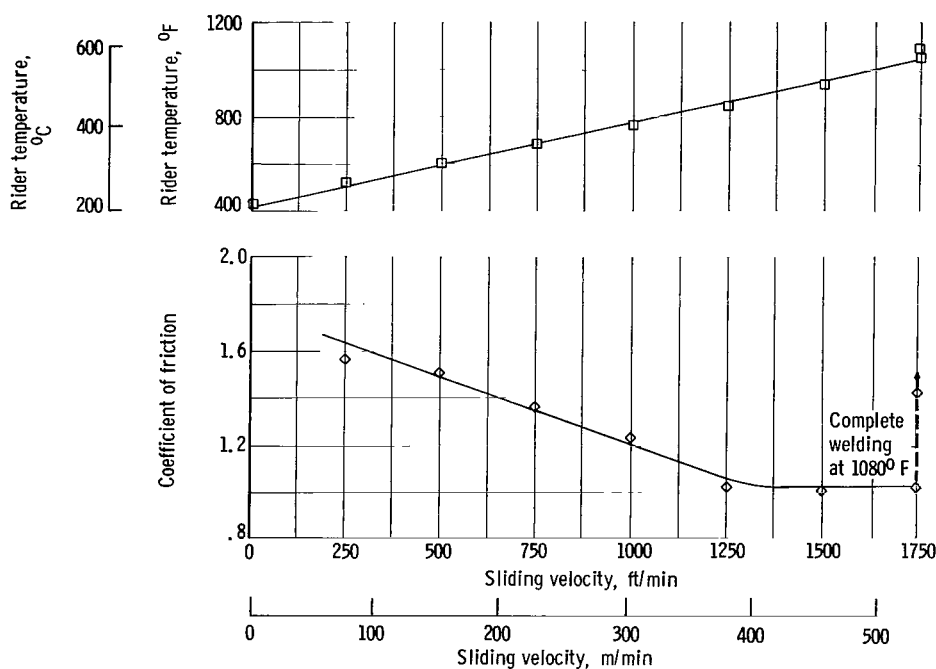


Figure 12. - Coefficient of friction and bulk rider temperature for a 50-atomic-percent-titanium - 50-atomic-percent-zirconium alloy sliding on itself in vacuum (10^{-7} mm Hg). Load, 750 grams; specimen starting temperature, 425° F.

periment with a rider specimen equipped with a thermocouple are shown in figure 12. The coefficient of friction decreased with increasing sliding velocity to 1250 feet per minute. At 1250 and 1500 feet per minute, the friction coefficient was about 1.0. At 1750 feet per minute, the coefficient of friction was approximately 1.0 at a temperature of 1050° F. As sliding continued, the temperature increased rapidly with a rapid increase in friction. The specimens then completely welded causing the magnetic drive to slip. The temperature recorded at this point was 1080° F.

The results of figure 12 indicate that, although the friction values for the hexagonal

titanium-zirconium alloy are high (1.0 or greater), they are less than are obtained when one of the specimens (rider) transforms to a cubic structure. With the rider alloy in the cubic form, complete welding to the disk occurred.

SUMMARY OF RESULTS

Based on the friction and wear data obtained in this investigation with titanium and simple binary titanium alloys (not bearing compositions) in vacuum, the following summary remarks can be made:

1. The coefficient of friction for titanium sliding on titanium and on 440-C stainless steel decreased with increasing sliding velocity or interface temperature apparently because of an increase in the c/a lattice ratio as well as influences exerted by other factors.

2. The friction and wear characteristics of titanium may be improved by alloying the titanium with tin. This alloying resulted in an increase of the c/a lattice ratio.

3. The friction coefficient for a titanium-zirconium alloy increased rapidly to complete welding and seizure of specimens when the alloy transformed from a hexagonal crystal structure to the cubic form. Although the slip pattern (multiple slip planes) for titanium more closely reflects cubic rather than ideal hexagonal behavior, marked differences in the friction characteristics for the titanium-zirconium alloy were observed with a crystal transformation from a hexagonal to a cubic structure.

4. The addition of 10 weight percent oxygen to titanium expanded the titanium crystal lattice parameter and resulted in improved friction characteristics and reduced welding and metal transfer.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 2, 1964.

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